

Evaluation analysis of the saturated paste method for determining typical coastal saline soil salinity

Qingyi Wang^{a,b}, Xiaobin Li^{c,*}, Chunhong Zhao^d, Liang Pei^{e,**}, Shuqin Wan^a

^a Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Science and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

^b University of Chinese Academy of Sciences, Beijing 100049, China

^c Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China

^d The water saving promotion center of the Ministry of Water Resources, Beijing 100038, China

^e Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China

ARTICLE INFO

Keywords:

Saturated paste extract
Electrical conductivity
Soil salinity
Soaking time
Adding water

ABSTRACT

The electrical conductivity of saturated paste extracts (EC_e) is more widely used as the laboratory method for estimating soil salinity compared to the soil-water ratio method. However, the current saturated paste process is time consuming and mainly based on subjective experience, and the quantitative relationships among the factors influencing the saturated paste process are not clear. In order to understand and optimize the process of soil salinity determination by saturated paste method, an experiment involving the process of making saturated paste and the key factors in salt determination was carried out on coastal saline silt and sandy loam soils: amount of water added, soaking time, number of centrifugations, and soil particle size. These test factors had clear impact on soil salinity results (both EC_e and mass salt content) and pH. Based on the principle of obtaining more mass salt content in this study, suitable parameters for the production of saturated slurries were proposed as follows: (1) the amount of distilled water added to the soil sample should be 2.2 times the saturated water content of the soil; (2) the equilibration time of saturated paste was reduced from 18 to 12 h; (3) only 40 % of the full salt content was obtained by one centrifugation and obtaining 80 % requires three centrifugations; and (4) 0.25–0.50 and 1–2 mm of particle-size sieving should be used to prepare samples of silt and sandy loam soils, respectively.

1. Introduction

Excessive accumulation of salts in the soil is considered a major impediment to sustainable agriculture (Qadir and Oster, 2002), and soils prone to salinization are found in different agricultural production regions of the world. Accumulation of excess salinity may cause soil slumping and impermeability, affecting the uptake and utilization of water and nutrients, making it difficult for crop roots to grow and causing stagnation and wilting of crops, thus radically reducing crop yields (Machado and Serralheiro, 2017; Minhas et al., 2020; Parihar et al., 2015). The classification and subsequent management of salt-affected soils worldwide, according to their degree of salinity, requires good knowledge of the quantity and distribution of soluble salts in the soil and therefore indices that adequately describe the state of soil

salinity. The electrical conductivity (EC) of soil solution extracts is widely used as a parameter for describing soil salinity and estimating ion concentrations in soils (Aboukila and Norton, 2017; Amakor et al., 2014). The EC provides a wealth of information about the moisture content and ionic composition of the soil. The salt content of the soil solution is positively correlated with EC within a certain concentration range, so the salt content of the soil can be measured using the magnitude of EC of the solution (Gharaibeh et al., 2021; Matthees et al., 2017).

Two extraction methods are currently widely used to assess soil salinity: saturated paste (SP) extraction and soil-water extraction (Aboukila and Norton, 2017). The SP method here differs from the “Bureau of Soils Cup” method in that the EC is not measured directly in the SP, but in the extracts of saturated soil for the determination of salts (Rhoades et al., 1989). By virtue of their ease of preparation and

* Correspondence to: Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, 12 A Zhongguancun South Street, Beijing 100081, China.

** Corresponding author.

E-mail addresses: lxbzch1314@163.com (X. Li), peiliang@igsnr.ac.cn (L. Pei).

<https://doi.org/10.1016/j.still.2022.105549>

Received 8 June 2022; Received in revised form 13 September 2022; Accepted 25 September 2022

Available online 6 October 2022

0167-1987/© 2022 Elsevier B.V. All rights reserved.

extraction, 1:1, 1:2, 1:2.5, 1:5, and 1:10 soil-water extracts are widely used by soil laboratories around the world to determine the EC values of soils (Amakor et al., 2014; Sonmez et al., 2008; Zhang et al., 2005). However, the soil-water extraction method is greatly affected by soil texture, and adding water has a significant impact on the measurement results. The SP method is more closely linked to natural soil conditions, taking into account the effect of dilution on ion concentration and conductivity induced by different soil-water ratios, and can minimize the effect of dilution on the degree of variation in ion ratios in natural soil solutions (He et al., 2013; Hogg and Henry, 1984; Khorsandi and Yazdi, 2011; Monteleone et al., 2016; Slavich and Petterson, 1993; Sonmez et al., 2008; Zhang et al., 2005). The EC of SP extracts (EC_e) is the best indicator of the response of plants to salinity, and is recommended as the standard laboratory method for estimating soil salinity (Herrero and Pérez-Coveta, 2005).

The current standard practice for preparing saturated pastes (SPs) in soil test chambers is based on the recommendation of USDA (Hide, 1954): a SP extract is prepared by adding a quantity of distilled water to a soil sample and stirring until it is completely saturated. When the SP has been equilibrated for 18 h, the vacuum extract is obtained by centrifugation, then filtered, and EC_e is measured at 25 °C using an EC meter. In the process of determining soil salinity using the SP method, the most critical aspect is determining the saturation point during SP preparation (Al-Busaidi et al., 2006). Saturation is determined to be sufficiently reproducible for SP when a homogeneous SP shines, flows slightly when turned, slides freely and cleanly off a smooth spade, appears as jars after forming a furrow, and satisfies a state of free water precipitation (Corwin and Yemoto, 2020; Rhoades et al., 1989). This places great demands on the operator's proficiency in preparing SP, requires some skill to estimate the correct saturation point, and also has an artificial impact on accuracy of the determination of soil salinity.

There is no unified standard for the amount of distilled water to be added to a SP and for its equilibration time. Considering that the ion concentration decreases with increasing dilution and that different amounts of less soluble salts are dissolved, the volume of distilled water added to the soil can bias the determination of salinity (Wallender and Tanji, 2011). Once the saturation point is reached, the SP needs to stand for a period of time to obtain internal ionic equilibrium, during which the corresponding physicochemical changes occur with the extension of time, which will likewise have an impact on the subsequent determination of salts. In addition, most soil laboratories extract the saturated liquid from the prepared SP after a single centrifugation for salt determination; however, is there any difference between the soil salinity characterized by the EC_e after one centrifugation and the actual soil salinity, and how great is the difference? Does the sieving particle-size of the soil sample for preparing SP affect the determination results? At present, there is no relevant quantitative and in-depth research.

In addition, The SP method is used to determine the EC values of soils by author's research team after years of experimental research on different types of saline soil in China (Li et al., 2015; Li and Kang, 2020; Sun et al., 2013; Wang et al., 2011), while found that different operators, the amount of water added, soaking time and other factors affect the soil salinity (EC_e) analysis results. Considering that the current saturated paste process is time consuming and mainly based on subjective experience, and the quantitative relationships among the factors influencing the saturated paste process are not clear (Amakor et al., 2014; Lek-sungnoen et al., 2011), an experiment involving the process of making saturated paste and the key factors in salt determination was carried out on coastal saline silt and sandy loam soils. The purpose of this study was to determine the specific effects of the abovementioned factors on the results of the various steps in the determination of soil salinity using the SP method, and to quantify the influence of parameters such as adding water, soaking time, centrifugation times, and sieving particle-size on soil salinity, so as to give suggestions on the selection of parameters for soil salinity determination by SP extraction method.

2. Materials and methods

2.1. Experimental site

Laboratory simulation experiments were conducted in December 2021 at the coastal wasteland station in the International Eco-City of Caofeidian District (39°20'N, 118°54'E), located in the south of Tangshan City, east China, and bordered to the north by Bohai Bay in the Pacific Ocean. The two soils used for the laboratory tests were selected from the International Eco-City and the Industrial Area of Caofeidian District, respectively, and are typical coastal saline soils with $EC_e > 4$ dS/m and sodium adsorption ratio (SAR) > 13 (mmol/L)^{0.5}. Soil samples collected in the field at a depth of 0–120 cm were air dried, ground, sieved through a 2-mm sieve, stored in plastic boxes and taken to the laboratory for analysis.

The EC_e of the two initial soils used in the experiment was 27.47 dS/m and 28.08 dS/m, respectively. In comparison, the SAR values of the international Eco-city soils are higher than those of the industrial area soils, 57.50 (mmol/L)^{0.5} for the former and 52.66 (mmol/L)^{0.5} for the latter. According to the US soil classification, the soil type in the Eco-City was silt soil, with 0.7 % clay (<0.002 mm), 80.13 % silt (0.002–0.05 mm), and 19.17 % sand (0.05–2 mm); while that in the Industrial Area was sandy loam soil, with 0.44 % clay, 43.52 % silt, and 56.04 % sand. The soil texture, EC_e , pH, and SAR of the two soils are shown in Table 1.

2.2. Experimental design

The potential main factors affecting EC_e were included in the study: treatments of adding water, soaking time, number of centrifugations, and soil particle size. Gradients were also set up in each treatment to differentiate the effects.

2.2.1. Water gradient test

The addition of the appropriate amount of pure water to the soil sample is the initial step in producing a SP. The SP preparation requires the operator to be skilled in the approximate range of water additions in order to determine whether the sample is ready to extract the supernatant after centrifugation. Under the traditional method of manual SP preparation, the amount of water added to the soil sample should be at least the saturated water content of the soil at a given capacity, otherwise, it will be difficult to extract the supernatant during centrifugation.

For coastal saline land, the soil capacity is generally more than 1.5 g/cm³, and in the process of its improvement and cultivation, the soil capacity is a changing process. Due to different improvement measures and time, it will be reduced to 1.3–1.5 g/cm³. In the preparation phase for conducting indoor trials, a quantity of each of the two soils was weighed into aluminum boxes and made up to a capacity of 1.3, 1.4, and 1.5 g/cm³, respectively, according to the ring knife method. The aluminum boxes used were all 100 cm³ in volume. The corresponding saturated water contents of the soil samples were measured by the drying method and converted to corresponding volumetric water contents. In comparison, the saturated water contents of both soils at different capacities did not significantly differ and the converted volumetric water contents fluctuated around 30 %. Consequently, 30 % was chosen as the saturated water content for both soils.

The volume of water added to the test tubes in this test used a gradient based on the previously measured saturation water content of the soil. The minimum threshold for water addition to a soil sample is determined by the saturation water content of the soil. There were 11 levels in the gradient of water addition (Table 2); each level was a multiple of the saturation water content of the soil, which was converted to the appropriate volumes of pure water and added to the soil sample and left to stand for a uniform 2 h before centrifugation.

The EC_e was determined by centrifuging the samples once under the same conditions and with different water addition levels to determine the trend of values. The results were used to determine the appropriate

Table 1Soil mechanical composition, EC_e [electrical conductivity of saturated paste (SP)], pH_s (pH of SP), and SAR (sodium adsorption ratio of SP) in the two initial soils.

| Soil source | Soil mechanical composition (%) | | | Soil texture | EC_e (dS/m) | pH_s | SAR (mmol/L) ^{0.5} |
|------------------------|---------------------------------|---------------|-----------|--------------|------------------|--------|--------------------------------|
| | < 0.002 mm | 0.002–0.05 mm | 0.05–2 mm | | | | |
| International Eco-City | 0.70 | 80.10 | 19.20 | Silt | 28.08 | 8.02 | 57.50 |
| Industrial Area | 0.44 | 43.52 | 56.04 | Sandy loam | 27.47 | 7.94 | 52.66 |

Table 2Water addition levels for saturated water content ($\theta_s = 30\%$).

| Level | W 1 | W 2 | W 3 | W 4 | W 5 | W 6 | W 7 | W 8 | W 9 | W 10 | W 11 |
|--------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Adding water | $1.0\theta_s$ | $1.2\theta_s$ | $1.4\theta_s$ | $1.6\theta_s$ | $1.8\theta_s$ | $2.0\theta_s$ | $2.2\theta_s$ | $2.4\theta_s$ | $2.6\theta_s$ | $2.8\theta_s$ | $3.0\theta_s$ |

range of water volumes to be added to the samples before the centrifugation.

2.2.2. Soaking time test

To produce a SP, soil samples should be soaked in pure water for a certain period before centrifugation. However, there is no clear range for the soaking time of soil samples in pure water, which is generally based on 24 h of infiltration. The general choice of time for equilibration of SP in soil testing laboratories worldwide is currently 18 h. The purpose of the soak test is to give a suitable soak time range so that the operator can judge the state of the SP and then flexibly adjust the test schedule during the determination of soil salinity using the SP method. A 30-g sample of both soils was weighed in each tube and a suitable amount of pure water was added according to the traditional SP preparation method, with the amount of water added being 1.5 times the saturated water content of that soil at a specific volume. There were 14 static immersion time levels (Table 3), with 2-h intervals for each level up to 24 h, and 1-day intervals for each level beyond 24 h.

The immersion treatments were carried out at the same ambient room temperature. After the pretreated tubes had reached the corresponding set soak times, a standard SP was made from the appropriate amount of soil in the tubes. The samples were centrifuged once and then the EC_e was measured to determine the appropriate soaking time before centrifugation to determine soil salinity.

2.2.3. Centrifugal count test

After the pretreatment step to produce SP (addition of pure water and static immersion), the SP in the test tube was centrifuged and the resulting supernatant at the top of the tube was extracted to determine soil salinity. In conventional SP preparation, the sample tube containing the SP is usually centrifuged only once, after which the operator extracts the supernatant for salinity and pH measurements or other indicators. Due to the dilution of ionic concentrations that occurs when different textured soils are prepared into saturated pastes, the measured salts in the supernatant after a single centrifugation are not representative of the original salinity of the whole soil sample, and the proportion of salts in the overall soil is determined following multiple centrifugation tests.

In this experiment, 30 g of each of the two soils were again weighed in test tubes, 1.5 times the saturated water content of water was added, and samples were static soaked in the same environment for 2 h prior to centrifugation. After soaking, soil samples from all tubes were placed in a centrifuge for several continuous, uninterrupted centrifugation tests.

At the end of each centrifugation, the supernatant of the tube was extracted for salinity and pH measurements, followed by the addition of the previously set amount of water, rapid modulation to a saturated

Table 3

Different levels of equilibration time for saturated pastes.

| Level | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 | T9 | T10 | T11 | T12 | T13 | T14 |
|------------|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|-----|
| Duration/h | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 48 | 72 |

paste and continued centrifugation, until the supernatant was extracted at the end of the last centrifugation of the sample met international ($EC_e < 4$ ds/m) and national standards ($EC_e < 2$ ds/m); the number of centrifugations required to meet these standards was determined. When the extracted supernatant had $EC_e < 2$ ds/m, all the salts in the soil sample were considered to have been extracted, at which point the centrifugation test was completed.

In addition, at the end of the single centrifugation, the supernatant was poured into an aluminum box and placed in an oven for 2 h at 150 °C. The mass of salt from the sample precipitated after a single centrifugation was determined by mass comparison before and after drying. After determining the number of centrifugations required for all salts to be extracted, the proportion of salts extracted by a single centrifugation relative to the total salt content of the sample was determined.

2.2.4. Soil particle-size test

The initial particle-size screening of the field-collected soil was required to facilitate the SP preparation. In the conventional SP preparation process, soil samples are often screened only once and their soil particle-size fixed (<1 mm). The operator pretreats the soil samples with water and immersion prior to centrifugation according to the default particle size.

Soil samples screened at different particle sizes also show differentiated characteristics in terms of their measured EC_e and pH in the supernatant after the SP has been prepared. The aim of this experiment was to investigate the association between these characteristics and particle size of the soils.

Small quantities of saline soils from the Eco-City and the Industrial Area were served according to different particle-size classes, producing five particle sizes (Table 4). The sieved soil samples were loaded into the corresponding tubes at a set volume (30 g) and pretreated before centrifugation (1.5 times the soil water content in water and 2 h static immersion time) under the same control conditions and in the same environment. The samples were centrifuged once and the EC_e and pH of the supernatant were measured to determine the specific aspects of the influence of soil particle size in the variation of salinity and pH of the SP.

2.3. Observation and measurements

The ring knife method was used to determine the saturation water content of the saline soils in the two study areas. This was done by fully saturating a ring knife with a soil sample for 24 h, laying a leachate layer underneath the ring knife and, when the gravity water was completely lost from the soil in its natural state within the ring knife, calculating the

Table 4
Different levels of particle sizes for making saturated paste soils.

| Level | S 1 | S 2 | S 3 | S 4 | S 5 |
|-------------------|-------------|-------------|-------------|-------------|-------------|
| Particle size /mm | 0.02 – 0.10 | 0.10 – 0.25 | 0.25 – 0.50 | 0.50 – 1.00 | 1.00 – 2.00 |

mass of capillary and gravity water within the soil by weighing before and after. From this calculation, the field water holding and saturated water contents of the two saline soils were determined.

The EC_e for each sample was determined using the method of USDA (1954). A SP extract was prepared by adding distilled water to a test tube containing approximately 30 g of soil sample and stirring until completely saturated. All soil samples were air dried in their natural state before being loaded into test tubes, and samples not involved in the soil particle-size test were additionally sieved using a 1-mm sieve. Soil particle-size tests were classified according to international systems. The EC and pH were determined using a conductivity meter (DDS-1 1 A, REX, Shanghai) and a pH meter (PHS-3 C, REX), respectively. The speed of the centrifuge was set at a uniform 2810 r/min for soil samples and the centrifugation time was ten minutes. The criterion for centrifugation was to separate the earth-water suspension in the test tube until the upper clear layer could be completely extracted.

In this test, for all samples from tubes that had been centrifuged at the end of the test, when the salinity and acidity of the extracted supernatant had been determined, the liquid was transferred into a dry aluminum box and dried in an oven at 150 °C for 2 h until solid particulate matter was evident in the box. The mass of salt content of the corresponding sample was determined by comparing weight before and

after drying.

2.4. Statistical analyses

Descriptive statistics (mean, standard deviation, and coefficient of variation) were used to describe EC_e and pH. All data collected in the study were recorded and classified in Microsoft Office Excel 2019. Analysis of variance (ANOVA) was performed using SPSS 21.0 statistical software (SPSS Inc., IL, USA). The significance of the effects of all variables was tested using one-way ANOVA.

Origin Pro 2022 (Origin Lab Inc., MA, USA) was used to describe how four key factors (water addition, soaking time, number of centrifugations, and soil particle size) affected the determination of EC_e and pH by the SP method, and to plot trends in EC_e and pH in the corresponding experiments.

3. Results

3.1. EC_e

The use of EC_e as an indication of the salinity status of the soil showed somewhat different results for the two soils in the four

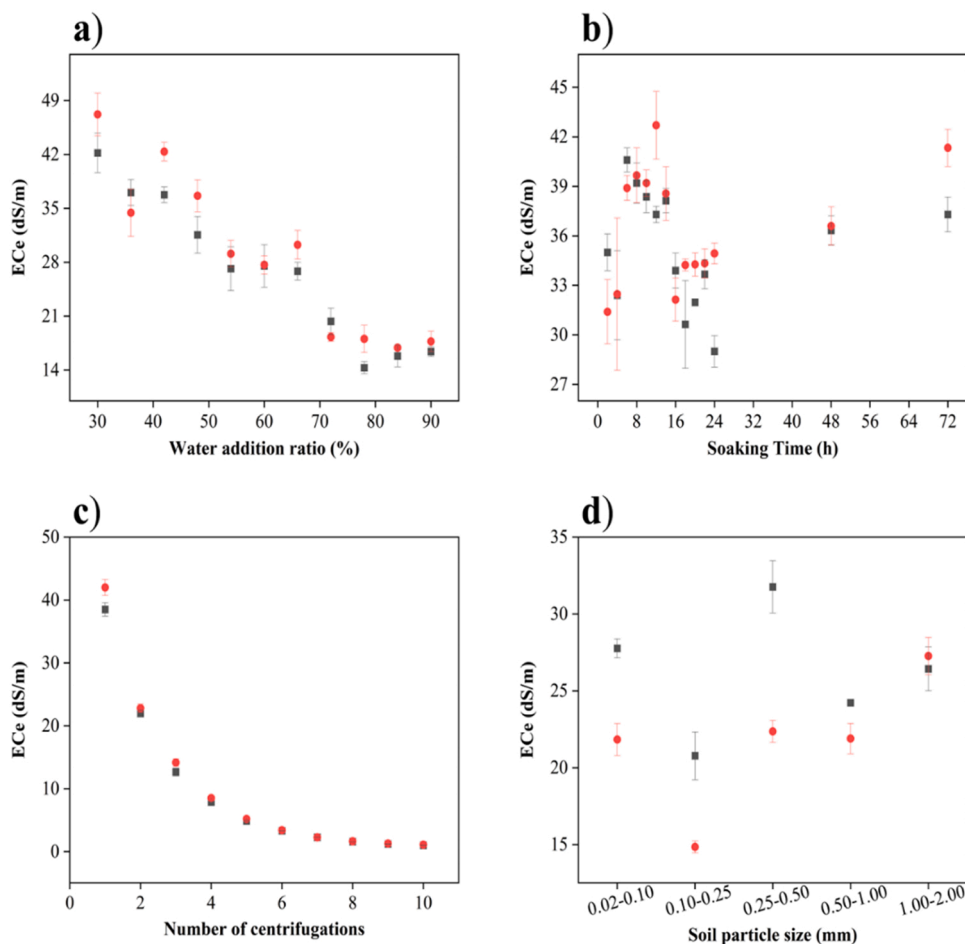


Fig. 1. EC_e in saturated paste supernatant of silt (■) and sandy loam (●) for treatments: (a) water addition; (b) soaking time, (c) number of centrifugations, and (d) soil particle size.

influencing factor tests. The centrifugation tests clearly showed that EC_e tended to decrease with increasing centrifugation (Fig. 1c). The EC_e of the supernatant of both soils after extraction reached international standards ($EC_e < 4$ ms/cm) after six centrifugations, at which point the EC_e of the saline soil in the Eco-City was 3.317 ms/cm and that for the Industrial Area was 3.407 ms/cm; after eight centrifugations, the national standard ($EC_e < 2$ ms/cm) was reached, at which point the EC_e of soil in the Eco-City was 1.582 ms/cm and that for the Industrial Area was 1.648 ms/cm. In addition, EC_e values for the supernatant after each centrifugation alone were significantly greater in the soil of the Industrial Area compared to that of the Eco-City.

In contrast, in the pretreatment of SP production, the EC_e of both soils showed a significant declining trend with increasing water addition (Fig. 1a). It is noteworthy that the EC_e of both soils first increased gently with increasing immersion time, and then gradually decreased after reaching a specific immersion time (Fig. 1b).

For the soil particle-size test, the EC_e of the two soil supernatants showed different trends. Overall, the EC_e of the soil supernatant in the Industrial Area tended to decrease and then increase as soil particle size increased, with the lowest EC_e of 14.85 ms/cm for particle size of 0.100–0.250 mm. There was no obvious trend for EC_e for the saline soil in the Eco-City (Fig. 1d).

3.2. pH

The pH in the supernatant of a SP can indicate the degree of acidity/alkalinity of the soil. In the water addition tests, the pH of the saline soils in the Eco-City rose gently as the amount of water added increased. In contrast, the soil from the Industrial Area reached a minimum pH of

7.027 when the amount of water added was 2.2 times the previously set saturated water content of the soil, and showed an overall fluctuating trend (Fig. 2a). In the immersion test, the pH of soil from the Industrial Area progressively declined with increasing soaking time, and stabilized at 12 h. The pH of the soil from the Eco-City decreased and then increased within 2–12 h of immersion; beyond 12 h of immersion, the pH decreased sharply and then rebounded to 7.307 by 72 h (Fig. 2b).

After centrifugation, the pH of the supernatant from both soils showed a significant increase, but with a faster increase in pH for Eco-City compared to Industrial Area soil (Fig. 2c). The pH of soil from the Eco-City increased with increasing soil particle size, while that for soil from the Industrial Area showed an increasing trend up to 0.250 mm and less variation in the two larger particle-size classes (Fig. 2d).

3.3. Mass salt content

Soil salinity was measured using both EC_e and mass salinity, and the two methods often showed different soil salinity statuses in the analysis of the supernatant extracted by the SP method.

Following addition of a certain amount of water, the quantity of extracted salt no longer increased, but decreased as the amount of water continued to increase. The specific amount of water added was a proportion of the previously measured soil saturated water content (i.e. 2.2 times), which was verified in both soils (Fig. 3a). This phenomenon was also seen in the immersion test. In the SP pretreatment, as soaking time increased, the amount of salt extracted from the soil supernatant initially increased and then ceased to increase after a certain period, with a possible decrease in the amount of salt extracted as soaking time continued (Fig. 3b).

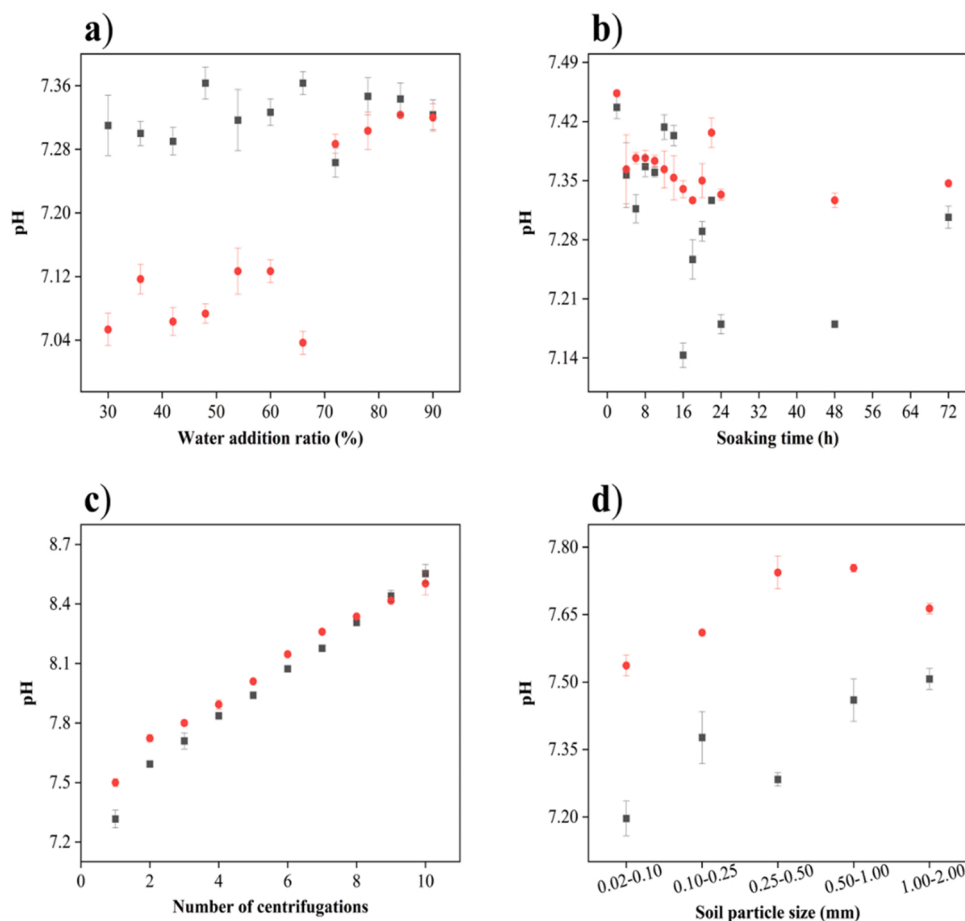


Fig. 2. The pH in saturated paste supernatant of silt (■) and sandy loam (●) for treatments: (a) water addition; (b) soaking time, (c) number of centrifugations, and (d) soil particle size.

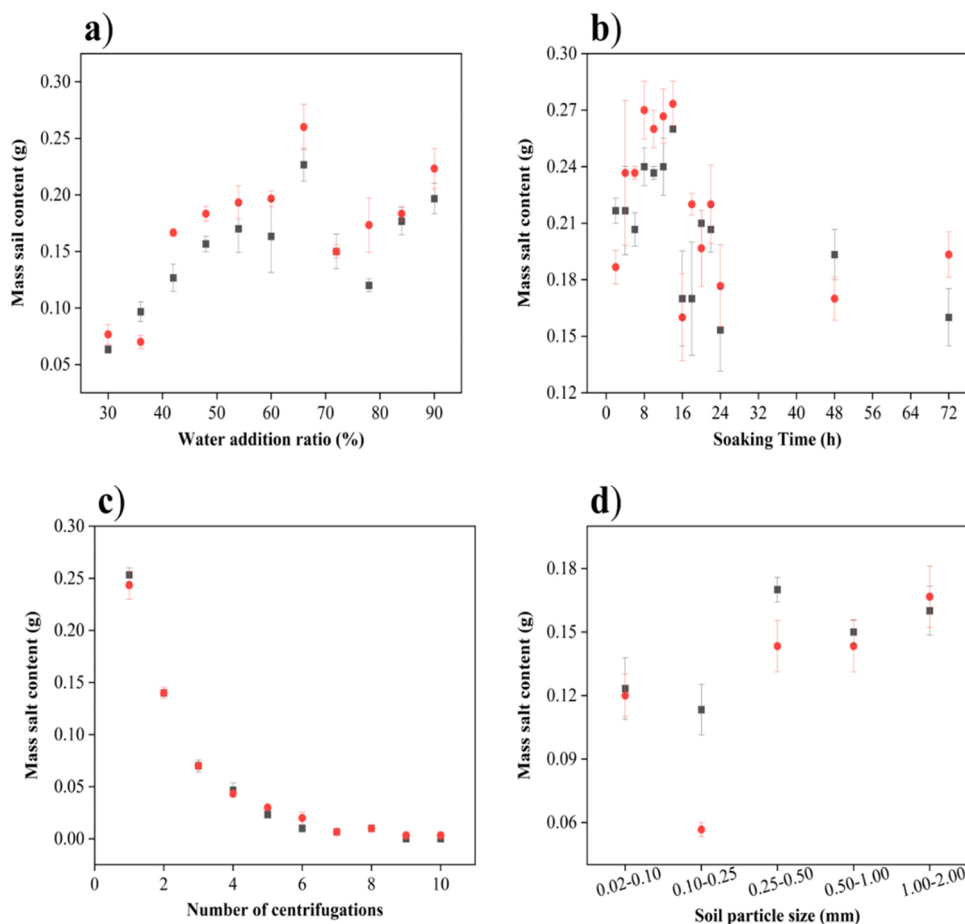


Fig. 3. Mass salt content in the saturated paste supernatant of silt (■) and sandy loam (●) for treatments: (a) water addition; (b) soaking time, (c) number of centrifugations, and (d) soil particle size.

The salt content in the supernatant of both soils increased as soil particle-size increased, although the rate of increase of the salt mass differed between the two soils, possibly related to the soil type and its mechanical composition (Fig. 3d). Furthermore, as is generally accepted, with more centrifugations, progressively less salt was extracted (Fig. 3c). For one conventional centrifugation, 40 % of the total salt content was obtained, and approximately 80 % of the total salt was extracted by the first three centrifugations (Fig. 4).

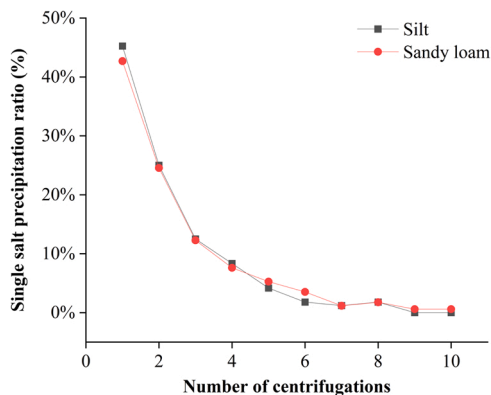


Fig. 4. Proportion of mass salt content to total salt content against number of centrifugations.

4. Discussion

4.1. Analysis of phenomena in SP preparation

The results showed that some phenomena in the process of SP production deserve further discussion and analysis. In view of the dilution effect, the addition of more distilled water to the soaking of the soil sample will inevitably lower the subsequent EC_e values, not only for the determination of salts using the SP method but also for the soil–water ratio method, as demonstrated in numerous studies (Aboukila and Norton, 2017; Kargas et al., 2020; Sonmez et al., 2008). For the different water addition levels, the EC_e and salinity by mass were lower for silt than for sand, probably because silt releases fewer ions during dissolution in the same SP state and the forces between soil particles are stronger than in sand. It is noteworthy that the water content of SP was about twice that of the soil and it was often difficult to make a SP with distilled water added to the soil sample below this threshold (Chi and Wang, 2010; Corwin and Yemoto, 2020).

The current SP in the soil test chamber needed to be equilibrated for 18 h. The results of this test showed that this criterion did not apply to all soils with different levels of salinity, and that the extension of the equilibration time affected the entry of salts adsorbed on soil particles into solution, as well as the chemical reactions at the atmosphere–solution contact surface. If the EC of the soil solution increases as the resting equilibration time increases, the ions break away from the surface of the soil particles and dissolve in the water; however, at high salt concentrations, ions with opposite charges in the solution can combine to form ion pairs with zero or other charges, and the formation of ion pairs may alter the salt measured in the SP, which explains why EC_e

decreased after a certain equilibration time was exceeded (Amakor et al., 2014; Herrero and Pérez-Coveta, 2005). As equilibration time continues to increase, ions from the atmosphere enter the soil solution and react with the corresponding ions in the SP in a displacement reaction, destroying the ion pairs and causing EC_e to rise instead.

In most soil laboratories, after SP has been produced, the supernatant is often extracted by filtering through filter paper or by direct centrifugation; however, often the full salt content of soil cannot be extracted by a single centrifugation and the salt value measured from the SP will be less than the actual salt content of the soil. We demonstrated that the first three centrifugations could extract 80 % of the actual salt content of the soil, while pH of the supernatant gradually increased with increased numbers of centrifugations, revealing that hydroxide ions adsorbed on the surface of the soil particles had a weaker association, and are more easily precipitated than H^+ . In addition, considering that the smaller the soil particles, resulting in a larger surface area per unit volume of soil particles carrying negatively charged groups, the more strongly the soil interacts with positively charged ions, which explains why in the saturated slurry method the measured conductivity and the precipitated salts are higher from silt than from sandy loam.

4.2. Suitable parameters for SP production

The SPs simulate the natural state of the soil solution and are associated with plant effects as this is the salinity actually experienced by plant roots, which naturally makes them the best indicator of soil salinity and the standard measure of salinity used in plant salinity tolerance studies (Khorsandi and Yazdi, 2011; van Zelm et al., 2020). However, SPs are more costly in terms of time and require a higher level of experience and skill, especially for clays and soils with a high organic content, and require skilled personnel to estimate the correct saturation point. The presence of free water on the SP surface, i.e. in a state of supersaturation, can lead to significant errors in the SP, although the effect on EC_e is minimal, and previous studies also raised concerns about the subjectivity of making saturated SPs (Gharaibeh et al., 2021; Longenecker and Lyerly, 1964; Zhang et al., 2005).

Based on the four experiments described above, we determined the parameters for optimizing the SP method for determining soil salinity. The parameters were selected on the basis of the principle that we consider the treatment to be more appropriate when the mass salt content obtained is higher under the different treatments. This is because the higher total salt content indicates that the water potential and ionic stress developed in this state may have a greater impact on the plant. In order to minimize the influence of subjectivity on the determination of soil salinity using the SP method, and to facilitate the ability of testers to rationalize the test schedule and reduce the need for judging the saturation point, we make the following four recommendations for the process of making SP, based on the results of the above tests.

Taking into account the subsequent values of EC_e and mass salinity, we recommend that the amount of distilled water added to the soil sample is 2.2 times the saturated water content of the soil, to be used to produce a SP;

The recommended equilibration time for SPs is 12 h ($P < 0.05$) in terms of time savings and prevention of SP contamination;

The current method of centrifugation for SP extracts only 40 % of the total salt content of the soil, which differs from its true salt content. To determine the true salt content of the soil using this method, at least 80 % of the salt content was obtained after three centrifugations. After eight centrifugations, the total salt content of the soil was stable;

The 0.25–0.50 and 1–2 mm of particle-size sieving should be used to prepare soil samples for silt and sandy loam soils, respectively.

5. Conclusion

As an effective means of monitoring soil salinity and assessing plant salt tolerance, the SP method is often compared with the soil-water ratio

method, and its time- and effort-consuming nature and difficulty in determining whether the SP is in a saturated state often affect the results of subsequent tests. By setting up tests with different levels in the key steps of the SP preparation process, and by combining the results of the tests to further investigate the phenomena, our tests provided a deeper understanding of the process of determining salinity in SPs, reduced time and costs for soil laboratory personnel, circumvented the most important aspect of the SP method (i.e. determining the saturation point), significantly reduced the influence of human subjectivity, and established a standard process for production of SPs. A standardized production process assists testers to avoid errors in subjectively judging saturation, flexibly adjusts the measurement schedule, reduces labor and time costs, and can provide a theoretical basis and strong support for monitoring soil salinity.

There are many types of saline soil all over the world, especially in China. Difference of influence from key factors in salt determination indeed was obtained in years of experimental research on different types of saline soil by authors. Coastal saline land is one of the important types of saline land in China, and coastal saline silt and sandy loam soils are the main type of coastal saline soil, thus these two soils are typical and representative for research. For other types of saline soil, the same experiment involving the process of making saturated paste and the key factors in salt determination is suggested to be carried out.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

This study was supported by the Special Project for Transformation of Scientific and Technological achievements of Inner Mongolia (2021CG0022), and the Agricultural Science and Technology Innovation Program (CAAS-ZDRW202201).

References

- Aboukila, E.F., Norton, J.B., 2017. Estimation of saturated soil paste salinity from soil-water extracts. *Soil Sci.* 182, 107–113. <https://doi.org/10.1097/SS.000000000000197>.
- Al-Busaidi, A., Yamamoto, T., Bakheit, C., Cookson, P., 2006. Soil salinity assessment by some destructive and non destructive methods in calcareous soils. *J. Jpn. Soc. Soil Phys.* 5, 15. <https://doi.org/10.1002/art.38902>.
- Amakor, X.N., Jacobson, A.R., Cardon, G.E., Hawks, A., 2014. A comparison of salinity measurement methods based on soil saturated pastes. *Geoderma* 219–220, 32–39. <https://doi.org/10.1016/j.geoderma.2013.12.010>.
- Chi, C.-M., Wang, Z.-C., 2010. Characterizing salt-affected soils of songnen plain using saturated paste and 1:5 soil-to-water extraction methods. *Arid Land Res. Manag.* 24, 1–11. <https://doi.org/10.1080/15324980903439362>.
- Corwin, D.L., Yemoto, K., 2020. Salinity: electrical conductivity and total dissolved solids. *Soil Sci. Soc. Am. J.* 84, 1442–1461. <https://doi.org/10.1002/saj2.20154>.
- Gharaibeh, M.A., Albalasmeh, A.A., El Hanandeh, A., 2021. Estimation of saturated paste electrical conductivity using three modelling approaches: traditional dilution extracts; saturation percentage and artificial neural networks. *CATENA* 200, 105141. <https://doi.org/10.1016/j.catena.2020.105141>.
- He, Y., DeSutter, T., Hopkins, D., Jia, X., Wysocki, D.A., 2013. Predicting EC_e of the saturated paste extract from value of $EC_{1:5}$. *Can. J. Soil Sci.* 93, 585–594. <https://doi.org/10.4141/cjss2012-080>.
- Herrero, J., Pérez-Coveta, O., 2005. Soil salinity changes over 24 years in a Mediterranean irrigated district. *Geoderma* 125, 287–308. <https://doi.org/10.1016/j.geoderma.2004.09.004>.
- Hide, J.C., 1954. In: Richards, L.A. (Ed.), *Diagnosis and improvement of saline and alkali soils*, 120. U.S. Salinity Laboratory Staff, U.S. Dept. of Agriculture, Washington, D.C.. <https://doi.org/10.1126/science.120.3124.800.a>
- Hogg, T.J., Henry, J.L., 1984. Comparison of 1:1 and 1:2 suspensions and extracts with the saturation extract in estimating salinity in saskatchewan soils. *Can. J. Soil Sci.* 64, 699–704. <https://doi.org/10.4141/cjss84-069>.

- Kargas, G., Londra, P., Sgoubopoulou, A., 2020. Comparison of soil EC values from methods based on 1:1 and 1:5 soil to water ratios and ECe from saturated paste extract based method. *Water* 12, 1010. <https://doi.org/10.3390/w12041010>.
- Khorsandi, F., Yazdi, F.A., 2011. Estimation of saturated paste extracts' electrical conductivity from 1:5 soil/water suspension and gypsum. *Commun. Soil Sci. Plant Anal.* 42, 315–321. <https://doi.org/10.1080/00103624.2011.538885>.
- Leksungnoen, N., Andriyas, T., Andriyas, S., n.d. ECe prediction from EC1:5 in inland salt-affected soils collected from Khorat and Sakon Nakhon basins, Thailand. *Communications in Soil Science and Plant Analysis* 12.
- Li, X., Kang, Y., 2020. Agricultural utilization and vegetation establishment on saline-sodic soils using a water–salt regulation method for scheduled drip irrigation. *Agric. Water Manag.* 231, 105995. <https://doi.org/10.1016/j.agwat.2019.105995>.
- Li, X., Kang, Y., Wan, S., Chen, X., Chu, L., 2015. Reclamation of very heavy coastal saline soil using drip-irrigation with saline water on salt-sensitive plants. *Soil Tillage Res.* 146, 159–173. <https://doi.org/10.1016/j.still.2014.10.005>.
- Longenecker, D.E., Lyerly, P.J., 1964. Making soil pastes for salinity analysis: a reproducible capillary procedure. *Soil Sci.* 97, 268–275. <https://doi.org/10.1097/00010694-196404000-00008>.
- Machado, R., Serralheiro, R., 2017. Soil salinity: effect on vegetable crop growth. Management practices to prevent and mitigate soil salinization. *Horticulturae* 3, 30. <https://doi.org/10.3390/horticulturae3020030>.
- Matthees, H.L., He, Y., Owen, R.K., Hopkins, D., Deutsch, B., Lee, J., Clay, D.E., Reese, C., Malo, D.D., DeSutter, T.M., 2017. Predicting soil electrical conductivity of the saturation extract from a 1:1 soil to water ratio. *Commun. Soil Sci. Plant Anal.* 48, 2148–2154. <https://doi.org/10.1080/00103624.2017.1407780>.
- Minhas, P.S., Ramos, T.B., Ben-Gal, A., Pereira, L.S., 2020. Coping with salinity in irrigated agriculture: crop evapotranspiration and water management issues. *Agric. Water Manag.* 227, 105832. <https://doi.org/10.1016/j.agwat.2019.105832>.
- Monteleone, M., Lacolla, G., Caranfa, G., Cucci, G., 2016. Indirect measurement of electrical conductivity and exchangeable cations on soil water extracts: assessing the precision of the estimates. *Soil Sci.* 181, 465–471. <https://doi.org/10.1097/SS.0000000000000181>.
- Parihar, P., Singh, S., Singh, R., Singh, V.P., Prasad, S.M., 2015. Effect of salinity stress on plants and its tolerance strategies: a review. *Environ. Sci. Pollut. Res.* 22, 4056–4075. <https://doi.org/10.1007/s11356-014-3739-1>.
- Qadir, M., Oster, J., 2002. Vegetative bioremediation of calcareous sodic soils: history, mechanisms, and evaluation. *Irrig. Sci.* 21, 91–101. <https://doi.org/10.1007/s00271-001-0055-6>.
- Rhoades, J.D., Manteghi, N.A., Shouse, P.J., Alves, W.J., 1989. Estimating soil salinity from saturated soil-paste electrical conductivity. *Soil Sci. Soc. Am. J.* 53, 6.
- Slavich, P., Petterson, G., 1993. Estimating the electrical conductivity of saturated paste extracts from 1:5 soil, water suspensions and texture. *Soil Res.* 31, 73. <https://doi.org/10.1071/SR9930073>.
- Sonmez, S., Buyuktas, D., Okturen, F., Citak, S., 2008. Assessment of different soil to water ratios (1:1, 1:2.5, 1:5) in soil salinity studies. *Geoderma* 144, 361–369. <https://doi.org/10.1016/j.geoderma.2007.12.005>.
- Sun, J., Kang, Y., Wan, S., 2013. Effects of an imbedded gravel–sand layer on reclamation of coastal saline soils under drip irrigation and on plant growth. *Agric. Water Manag.* 123, 12–19. <https://doi.org/10.1016/j.agwat.2013.03.004>.
- Wallender, W.W., Tanji, K.K. (Eds.), 2011. *Agricultural Salinity Assessment and Management*, Second edition. American Society of Civil Engineers, Reston, VA. <https://doi.org/10.1061/9780784411698>.
- Wang, R., Kang, Y., Wan, S., Hu, W., Liu, Shiping, Liu, Shuhui, 2011. Salt distribution and the growth of cotton under different drip irrigation regimes in a saline area. *Agric. Water Manag.* 100, 58–69. <https://doi.org/10.1016/j.agwat.2011.08.005>.
- van Zelm, E., Zhang, Y., Testerink, C., 2020. Salt tolerance mechanisms of plants. *Annu. Rev. Plant Biol.* 71, 403–433. <https://doi.org/10.1146/annurev-arplant-050718-100005>.
- Zhang, H., Schroder, J.L., Pittman, J.J., Wang, J.J., Payton, M.E., 2005. Soil salinity using saturated paste and 1:1 soil to water extracts. *Soil Sci. Soc. Am. J.* 69, 1146–1151. <https://doi.org/10.2136/sssaj2004.0267>.